

# X-Ray and Radio Emission from the Luminous Supernova 2005kd

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## ABSTRACT

SN 2005kd is among the most luminous supernovae (SNe) to be discovered at X-ray wavelengths. We have re-analysed all good angular resolution (better than 20'' FWHM PSF) archival X-ray data for SN 2005kd. The data reveal an X-ray light curve that decreases as  $t^{-1.62 \pm 0.06}$ . Our modelling of the data suggests that the early evolution is dominated by emission from the forward shock in a high-density medium. Emission from the radiative reverse shock is absorbed by the cold dense shell formed behind the reverse shock. Our results suggest a progenitor with a mass-loss rate towards the end of its evolution of  $\geq 4.3 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ , for a wind velocity of  $10 \text{ km s}^{-1}$ , at  $4.0 \times 10^{16} \text{ cm}$ . This mass-loss rate is too high for most known stars, except perhaps hypergiant stars. A higher wind velocity would lead to a correspondingly higher mass-loss rate. A Luminous Blue Variable star undergoing a giant eruption could potentially fulfill this requirement, but would need a high mass-loss rate lasting for several hundred years, and need to explain the plateau observed in the optical light curve. The latter could perhaps be due to the ejecta expanding in the dense circumstellar material at relatively small radii. These observations are consistent with the fact that Type IIn SNe appear to expand into high density and high mass-loss rate environments, and also suggest rapid variability in the wind mass-loss parameters within at least the last 5000 years of stellar evolution prior to core-collapse.

**Key words:** circumstellar matter; stars: mass-loss; supernovae: individual: SN 2005kd; stars: winds, outflows; X-rays: individual: SN 2005kd; X-rays: individual: SN 2006jd

## 1 INTRODUCTION

The core-collapse of a massive star greater than about  $8 M_{\odot}$  results in a spectacular explosion, and the expansion of a very high velocity shock wave into the ambient medium, leading to the formation of a supernova (SN) of Type II or Type Ib/c. Type II SNe are further divided into different subclasses, depending mainly on their optical spectra or light curve. Type IIn SNe form one of the more recent subclasses of Type II SNe, having been first identified in 1990 (Schlegel 1990). They are characterized by narrow lines on a broad base in the optical spectrum (Schlegel 1990; Kankare et al. 2012; Mauerhan et al. 2013). Surveys have revealed that they comprise between 1 and 4% of the total core collapse SN population in a volume limited sample (Eldridge et al. 2013). Observations at optical (Filippenko

1997; Taddia et al. 2013), infra-red (Fox et al. 2011), X-ray (Dwarkadas et al. 2010; Chandra et al. 2012), and radio (Chandra et al. 2009, 2012) suggest that this class of SNe arises from circumstellar interaction with a high-density medium. Spectropolarimetric observations of luminous IIns (Bauer et al. 2012) are consistent with circumstellar interaction, but point to a complex origin for the various emission components.

There exists a wide diversity in SNe that exhibit IIn features, which has greatly complicated the task of identifying their progenitors. The prototypical IIns SN 1986J, SN 1988Z, and SN 1978K were only observed years after explosion. More recently transient surveys have found SNe that show IIn-like features very early in their evolution. Despite over two decades of study, no consensus has been reached on the identity of their progenitor stars, and it seems quite likely that the class of IIns does not have one class of progenitors. Luminous Blue Variable (LBV) stars have been

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suggested as the progenitors of IIns (Gal-Yam & Leonard 2009; Smith 2010), although this has been disputed by some authors (Dwarkadas 2011). Analysis of some IIns led Dwarkadas (2011) to suggest that RSG stars that undergo high mass-loss at the end of their lifetimes could be IIn progenitors, while Smith et al. (2009) have suggested extreme RSGs such as VY CMa as Type IIn progenitors. Thus, although many theories exist, identifying the progenitors will require observations and analysis of a large sample of Type IIns over the entire wavelength spectrum.

Supernova 2005kd was discovered in an automated search by Puckett & Pelloni (2005) on 2005 Nov 12.22 UT. It was confirmed by Eastman et al. (2005) to be a Type IIn SN. It lies in the galaxy LEDA 14370, at a redshift of  $z=0.015040$ , which translates to a luminosity distance of about 63.2 Mpc ( $H_0=71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_{\text{matter}} = 0.27$ ,  $\Omega_{\text{vacuum}} = 0.73$ ). X-ray and UV emission was observed at the position of the SN with Swift in January of 2007 (Immler et al. 2007). Following this, X-ray emission was detected with *Chandra* (Pooley et al. 2007). The SN was also detected in the radio band at 8.4 GHz (Chandra & Soderberg 2007). This is one of the furthest SNe to be detected in X-rays, suggesting an unusually high X-ray luminosity. SN 2005kd was observed in the infra-red by the WISE satellite, however the detection is questionable due to the proximity of the host nucleus (Fox et al. 2013; Fox 2015).

The optical lightcurve of SN 2005kd (Tsvetkov 2008) shows an unusually long plateau stage, unique for a Type IIn SN, which lasted for at least 192 days. The UV lightcurves (Pritchard et al. 2014) show an even larger timespan where the flux appears to be either constant or even increasing. Clearly, even for the strange class of Type IIn's this represents a unique evolution.

In this paper we re-analyse and present all available X-ray data on SN 2005kd, combined with a 29 ks *Chandra* spectrum that we obtained in Nov 2013. We use this data to study the evolution of the X-ray light curve, the nature of the X-ray emission, the density structure of the surrounding medium, and thereby the mass-loss properties of the progenitor star. In §2 we summarize the available data, and describe the X-ray data reduction and fitting methods. §3 presents the X-ray lightcurve of SN 2005kd. In §4 we interpret the lightcurve using semi-analytic calculations, use it to extract information regarding the medium which the SN is expanding in, and attempt to delineate the SN progenitor. Motivated by the results from this section, in §5 we present available radio archival data that we have reduced and analysed in order to improve our understanding of the SN evolution. Finally, §6 summarizes our work, and places this SN in the context of other IIn SNe as well as the complete group of core-collapse SNe.

## 2 DATA ANALYSIS

SN 2005kd was first detected in the X-ray band around 15 months after explosion, and thus no data exist for the first year of evolution. We have reduced all good angular resolution ( $< 20''$  FWHM PSF) data, including data from *Swift*, *Chandra* and *XMM-Newton*. The exposure times in general were short, such that much of the data has low signal-to-

noise. Table 1 summarizes the available data and lists the derived fluxes.

The data from each satellite was reduced according to the standard reduction procedures. X-ray spectral fitting was done using SHERPA with thermal XSPEC models. We have presented results using the *vmekal* models, but note that using either *raymond* or *apec* models does not alter the derived conclusions. Given the low number of data counts in all cases except for the *XMM-Newton* pointing, all fits and flux estimations were done by fitting the background first using a polynomial function, and then simultaneously fitting the data plus the background, using the *cstat* statistic on unbinned data. The high statistics of the *XMM-Newton* observation allowed use of the *chi2gehrels* statistic on binned data combined with background subtraction. The flux estimates are shown in Table 1. Below we discuss the data reduction and analysis in detail.

### 2.1 XMM-Newton

The SN was observed at an age of 500 days using *XMM-Newton*. This is the longest exposure, with by far the best spectral resolution and effective area, and was used as a template for the subsequent data reduction. The  $> 600$  source counts allow for a reliable fitting of the spectrum, providing the model template that we adopted to fit all the other spectra. A  $25''$  region was used for the source, with the background region being of the same size several arcseconds away. The data were appropriately filtered and spectra obtained using version 14 of the XMM-SAS software, following standard data reduction procedures. The *Chandra* SHERPA software (Freeman et al. 2001) was used for analysis and fitting of all spectra. All the three datasets were fitted simultaneously to ensure the tightest constraints. Figure 1 shows the spectra from the MOS1, MOS2 and PN instruments on board XMM, together with a thermal *vmekal* model that was used to jointly fit the three spectra. A Ca line at 4 keV can be seen. The presence of lines indicated that a thermal model was appropriate. In the fits we find that allowing Ca, Ar, and Fe to deviate from solar values allows for the best fit. These elements were allowed to float freely but linked to have the same values in the MOS spectra, with only the normalization varying freely in each case. As can be seen from Figure 1, the best-fit normalization is quite similar for MOS1 and MOS2. In general with all the fits, it is clear that allowing the  $\alpha$ -element values to float freely tends to improve the fit. The best-fit abundances in both the MOS and PN fits were found to be higher than solar, with Fe and Ar having enhanced values  $> 10$  (in terms of Anders & Grevesse (1989) solar values), and Ca showing even larger abundances but with an equally large  $1-\sigma$  variation:  $280 \pm 279$ . The MOS fits did not change appreciably with S thawed, but the PN fit demanded values of  $S > 10$ . The best-fit temperature is high, beyond the measurable range of *XMM-Newton*. In each case we have used a single temperature model, which seems to match the spectra well. The best fit column density is found to be  $9.4 \pm 0.29 \times 10^{21} \text{ cm}^{-2}$ , consistent with the trend seen earlier. Unabsorbed fluxes are listed in Table 1. The error on the flux was computed using the *Sherpa sample\_flux* routine, which computes the flux (typically) 1000 times, taking the variations in the parameters into account, and then de-

**Table 1.** Summary of X-ray Data on SN 2005kd, listing the satellite which took the observation, the rest-frame corrected days after explosion, the exposure time, the column density and derived temperatures, and k-corrected unabsorbed fluxes, all with  $1\text{-}\sigma$  error bars where available.

Satellite	Obs Date	Days After Outburst <sup>a</sup>	Days After Outburst (Rest Frame)	Exposure (ks)	Count Rate ( $10^{-3}$ counts $\text{s}^{-1}$ )	$N_H$ ( $10^{22} \text{cm}^{-2}$ )	kT keV	0.3 - 8 keV Flux <sup>b</sup> ( $10^{-14}$ $\text{erg s}^{-1} \text{cm}^{-2}$ )
<i>Swift</i>	2007-01-24	440	433.5	8.9	$3.9 \pm 0.7$	$0.4 \pm 0.27$	$17 \pm 7$	$26^{+13}_{-11}$
<i>Chandra</i>	2007-03-04	479	472.0	3.0	$22 \pm 2.7$	$0.77 \pm 0.17$	$> 20$	$49.6^{+27}_{-16.8}$
<i>XMM</i> <sup>c</sup>	2007-03-29	504	496.5	54.2	$15 \pm 0.7$	$0.94 \pm 0.29$	$> 30$	$41.4^{+4.1}_{-9.4}$
<i>Chandra</i>	2008-01-03	784	772.4	5.0	$17 \pm 1.8$	$0.95 \pm 0.49$	$6 \pm 0.1$	$44.6^{+25.3}_{-25.3}$
<i>Swift</i>	2008-08-21	1015	1000.0	9.3	$2.2 \pm 0.5$	$0.75^d$	$4.9^{+35}_{-2.3}$	$19.86^{+1.87}_{-6.93}$
<i>Swift</i>	2011-10-22 to 2012-01-05	2200	2167.4	9.9	0.96	$0.4^d$	$3.5^d$	$< 6.7$
<i>Swift</i>	2012-06-01 to 2012-07-16	2419	2383.0	16.5	$0.7 \pm 0.3$	$0.15^{e+0.15}_{min}$	$4.4^f [+75.5]_{-2.9}$	$3.35^{+0.18}_{-1.65}$
<i>Chandra</i>	2013-11-29	2940	2896.5	29.0	$2.4 \pm 0.4$	$0.43^{+0.12}_{-0.28}$	$3.12^{+30}_{-0.4}$	$1.98^{+0.44}_{-0.36}$

<sup>a</sup> average value in case of combined exposures

<sup>b</sup> using cstat statistic (except *XMM-Newton*)

<sup>c</sup> average MOS1, MOS2

<sup>d</sup> assumed

<sup>e</sup> converges to minimum set value (Galactic value)

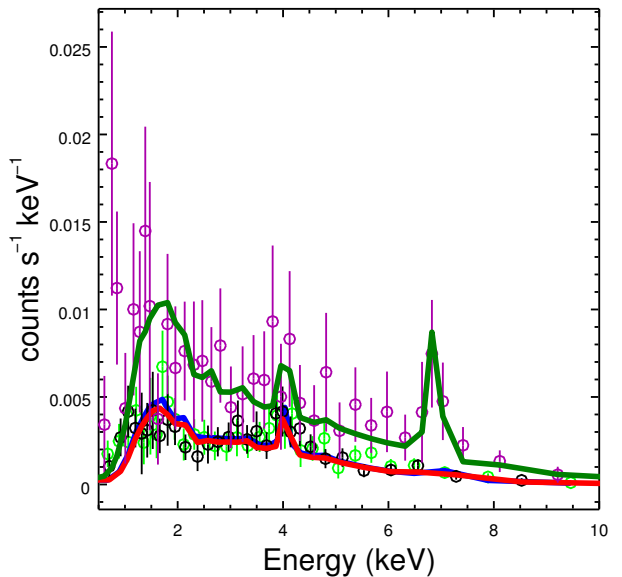
<sup>f</sup> upper bound unconstrained

termines the average flux and  $1\text{-}\sigma$  error from the computed fluxes.

We also attempted to fit a two temperature model to the *XMM-Newton* data, tying the abundance values of the two components together. The two temperature model results in a very low second temperature component as it tries to mainly fit the low temperature region, giving temperatures around 0.2 keV. It does not change the fit appreciably, but increases the unabsorbed flux considerably, because the high column density results in an unabsorbed flux at low temperatures that significantly exceeds the absorbed flux. We do not consider these models viable, and they do not improve the fit in the high-temperature region. It is possible that allowing the abundance values of each component to vary completely independently of the other may provide a better fit. This also significantly increases the parameter space and fitting time however. Our main purpose in this paper is to get a reasonable fit in order to estimate the flux and luminosity from the SN, and calculate the light curves. We have found that the 1-component fits are adequate for this purpose. The fluxes so obtained are consistent within the error bars with those listed in the *XMM-Newton* Serendipitous Source Catalogue, 3XMM-DR4, further validating our choice of model and fits. Finally, some of the assumptions inherent to our model, such as ionization equilibrium, are validated in §4.

## 2.2 Swift

SN 2005kd was observed several times between 2007 and 2012 with the *Swift* X-ray Telescope (XRT), which has a  $23' \times 23'$  field-of-view,  $18''$  FWHM PSF (although the 90% encircled energy diameter is  $\approx 43''$  with mild energy dependence), and provides spectra over the 0.3-8.0 keV band with



**Figure 1.** *XMM-Newton* MOS1, MOS2 and PN data and fits. All datasets were fitted simultaneously using the same thermal *vmekal* model, and required abundances of Ca, Ar and Fe in excess of solar values. MOS1 data is in light green, and the corresponding fit in blue. MOS2 data is in black, and the fit in red. The PN data is in purple with the fit in dark green. The similarity in the fits demonstrates that the same model adequately fits all datasets simultaneously. The Fe-K $\alpha$  line at 6.7 keV is visible in the PN data alone, a result of the effective area differences between the MOS and PN detectors at 6.7 keV.

a spectral resolution of  $\approx 0.1\text{--}0.2$  keV. Processed data were retrieved from the *Swift* archive. A  $35''$  region was used to extract the data, with the background obtained from a larger annulus region of  $35\text{--}100''$ . Analysis was performed using FTOOLS and custom software. We filtered for event grades 0–12 only, used the standard XRT response matrix, and generated a position-dependent ancillary response file using the FTOOL program *xtmkarf*, which provides nominal vignetting and PSF aperture corrections. Spectra close enough in time were binned together to provide sufficient signal-to-noise, as listed in Table 1.

Figure 2 shows images from 4 different epochs during which *Swift* data were obtained. The SN was detected in 2007 and 2008 with a significance  $> 6\sigma$ . In 2012 it was detected again but the significance was low ( $\approx 3.3\sigma$ ), prompting us to request a follow-up *Chandra* observation. The *XMM-Newton* and *Chandra* spectra reveal that the spectrum is clearly thermal in origin. Consequently for those epochs where the SN was detected, we fitted the spectra using a single *vmekal* model. We note that the flux obtained for the 2007 dataset is almost identical to that obtained by Immler et al. (2007). Our error bars are larger, which is understandable given that we actually fit the spectrum, rather than assuming a priori a thermal plasma with a temperature  $kT=10$  keV, and a Galactic  $N_H$  of  $1.5 \times 10^{21} \text{ cm}^{-2}$  (Dickey & Lockman 1990). The best-fit temperature is high ( $17 \pm 7$  keV). The column density is also higher than that used by Immler et al. (2007), but due to the higher temperature tends not to have as much of an effect on the flux. We find that the column density in the 2007 dataset is  $4.0 \pm 2.8 \times 10^{21}$  (over twice the Galactic value).

The 2008 dataset initially gives a very high value of the column density ( $> 4.0 \times 10^{22} \text{ cm}^{-2}$ ), which results in an extremely high value of the unabsorbed flux ( $> 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ ), using either statistic. This value seems quite out of place with the previously obtained values, suggesting a sudden increase in column density, whereas the general trend seems to be slowly decreasing. However, plotting the variation of the column density versus temperature in the background fitted model shows that the  $1\text{-}\sigma$  range of possible values is large. By fixing the column to a much smaller value of  $7.5 \times 10^{21} \text{ cm}^{-2}$  (intermediate between the two nearest values, but closer to the previous *Chandra* value), we find an almost equally good fit, with a flux that is an order of magnitude smaller. We have chosen to use this lower flux, which is more appropriate. We can reduce the column somewhat more, but the effect on the flux is within the error bars.

In 2011, the SN was not detected by *Swift* during an aggregate 9.3 ks XRT observation. Upper limits to the flux were calculated using the Bayesian method of Kraft et al. (1991) for 99% confidence. The uniform prior used by these authors results in fairly conservative upper limits, and other reasonable choices of priors do not materially change our scientific results. Within  $35''$ , there are 4 counts, of which 3 are expected to be background based on a larger annulus region of  $35\text{--}100''$ , once we scale by the source-to-background area difference. Using the Kraft et al. (1991) upper limits for this source + background, we derive a 99% upper limit of 8.9 counts. With an exposure of 9.3 ks, this equates to  $9.6 \times 10^{-4} \text{ counts s}^{-1}$ . Using the *Chandra* PIMMS calculator, we deduce an upper limit of  $4.0 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$ . This upper limit is for the observed or absorbed flux. In order

to get the unabsorbed flux, we used the *Chandra* PIMMS calculator, assuming an  $N_H = 4.0 \times 10^{21} \text{ cm}^{-2}$  (again based on a decreasing  $N_H$  within the 2008 and 2012 values) and a temperature of 3.5 keV (intermediate between neighbouring values). A much lower temperature could increase the flux by about 30–40%, but we think this is a better estimate given the parameters for the other observations closest in time. This gives an unabsorbed flux limit of about  $6.7 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$ .

By 2012 the column density seems to have dropped to a value approaching the Galactic value, the temperature has decreased, and the flux is lower, as seen in Figure 3.

### 2.3 Chandra

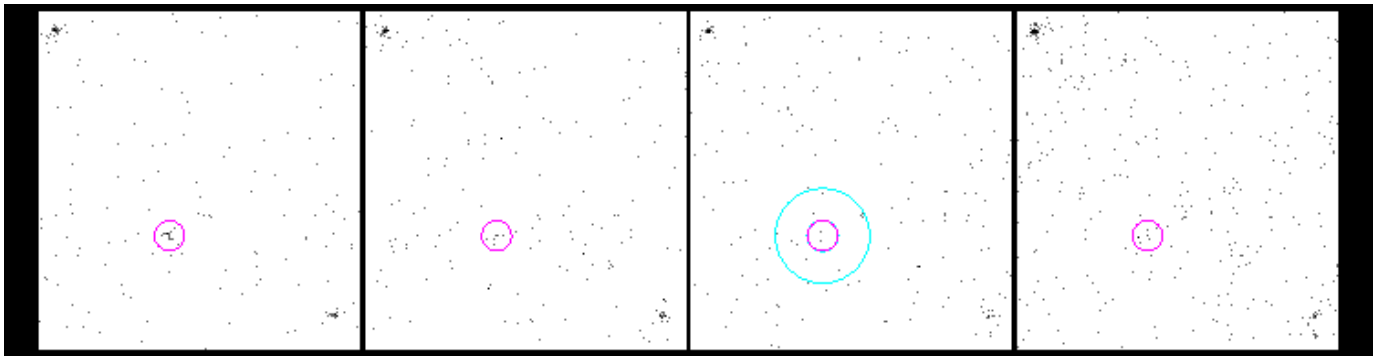
SN 2005kd was observed three times with the ACIS-S instrument on *Chandra*. Observations of 3 and 5 ks were made in 2007 (ObsID 8518) and 2008 (ObsID 9095), respectively. Even in these short observations, the SN was easily detected with  $> 13\sigma$  significance. After the SN was re-detected by *Swift* in 2012, we proposed for, and were awarded a 30 ks observation, which was carried out in Nov 2013 (ObsID 15999). The SN is detected with  $> 7\sigma$  significance, thus confirming the *Swift* re-detection.

The *Chandra* data were reduced and analyzed using the analysis pipeline in the CIAO software version 4.7, and CALDB 4.6.8. A 4-arcsec source region centered on the point source was used. Our spectra were fitted with a thermal plasma *vmekal* model with a variable temperature and column density. Given the results from the *XMM-Newton* fitting, we thawed elements Ca and Fe, as well as Si. The C-statistic decreases, and the fit improves, when these elements are thawed. We find abundance values of Fe and Ca similar to those obtained with *XMM-Newton*, with Ca once again resulting in highly elevated abundance values with large error bars. For ObsID 8518, this gives a flux that is larger than the 2007 *Swift* value by almost 80%. We note that Pooley et al. (2007) fitted a power-law model to the data, found a column density comparable to the Galactic one and a luminosity about 85% higher than their *Swift* value, so these results are quite consistent. Our best fit gives a column density  $7.7 \pm 1.7 \times 10^{21} \text{ cm}^{-2}$ , which is higher than the Galactic column density. The best fit also suggests that the abundance of metals such as Fe and Ca exceeds the solar value.

SN 2005kd was observed again by *Chandra* 10 months later. The same thermal model was used as for the prior *Chandra* dataset. We find the column density is  $9.5 \pm 4.9 \times 10^{21} \text{ cm}^{-2}$ , an elevated Ca abundance exceeding solar, and temperature of  $\sim 6$  keV.

Finally, SN 2005kd was observed using ACIS-S on *Chandra* in Nov 2013. As mentioned before, the SN was detected with a high significance, confirming its reappearance since 2011. The best fit thermal model gives a  $kT = 1.47 \pm 0.39$  keV, and  $N_H = 4.3 \pm 1.11 \times 10^{21} \text{ cm}^{-2}$ , with a preference for an elevated Si abundance. The column density is somewhat higher than the *Swift* 2012 value. The temperature is slowly decreasing as expected, since the higher temperatures in the first 500 days.





**Figure 2.** Images from the *Swift* observations of SN 2005kd, in the 0.3-8 keV energy range. From left to right: 2007, 2008, 2011 and 2012. The region is  $11.5'$  on each side. The pink circle ( $35''$  in radius) denotes the region used to extract the data for SN 2005kd. The annulus used for the background region is shown in blue in the 2011 panel. Clearly, the SN is not detected in 2011, but it is detected in all the other frames.

### 3 X-RAY LIGHTCURVE

Figure 3 (top panel) shows the complete X-ray lightcurve of SN 2005kd calculated using background fitting. The data are converted to the rest frame epoch, and k-corrected unabsorbed flux is plotted. The fluxes are calculated as indicated above, with  $1-\sigma$  error bars. Subsequent to the 2008 *Swift* observation, for over a 1000 days, there were no X-ray observations of SN 2005kd. We have combined exposures from Oct 2011 to Jan 2012 to get a combined almost 10 ks exposure with *Swift*. The SN is not detected at all within this exposure. However it is in the next two exposures, with *Swift* and *Chandra*.

SN 2005kd represents one of the most X-ray luminous Type IInS. Figure 4 shows the lightcurve of other observed Type IIn SNe. The X-ray lightcurve of SN 2005kd is shown as a thick black line. The upper limit from the *Swift* 2011 observation is not shown. It is clear that SN 2005kd is one of the most luminous, even among Type IIn SNe, with a luminosity exceeding  $10^{40}$  ergs  $s^{-1}$  over a period of about 550 days starting from day 440. The total energy deposition, in the 0.3-8 keV X-ray band alone, from days 400 to about 3000 is  $> 10^{49}$  ergs. The total energy in X-rays is likely to be much larger given the high temperatures inferred from spectral modelling. This means that the SN radiated more than 1% of its kinetic energy within the first 3000 days at X-ray wavelengths, unless the kinetic energy substantially exceeds  $10^{51}$  ergs. Tsvetkov (2008) had calculated a lower limit to the energy radiated at optical wavelengths, finding it to be  $3.2 \times 10^{50}$  ergs in the first 500 days. Either the SN is radiating away a large fraction of its energy in its first decade, or the total kinetic energy exceeds the canonical  $10^{51}$  ergs by a substantial margin.

### 4 ANALYSIS AND INTERPRETATION

The overall lightcurve of SN 2005kd from 440 to 3000 days indicates a decreasing luminosity with time. If we assume, as is generally the case, that the light curve decays as a power-law in time, the best fit to the data points gives a lightcurve that decreases as  $t^{-1.62 \pm 0.06}$  (Figure 3). The temperature suggested by the first 4 epochs is higher than the range of values that can be measured by *Chandra*, *XMM-*

*Newton* and *Swift*, and is thus relatively unconstrained. The column density is higher than the Galactic  $N_H$  towards that direction ( $1.5 \times 10^{21}$   $cm^{-2}$ ) by a factor of 3-10, and appears to slowly decrease over time within the (large) error bars. At  $\sim 1000$  days, the best fit spectral model suggests a lower temperature and higher column density, but plotting the 2D confidence contours of temperature vs. column density indicates that it is also compatible with the previous observations of a high temperature and  $N_H$  around 5 times the Galactic value.

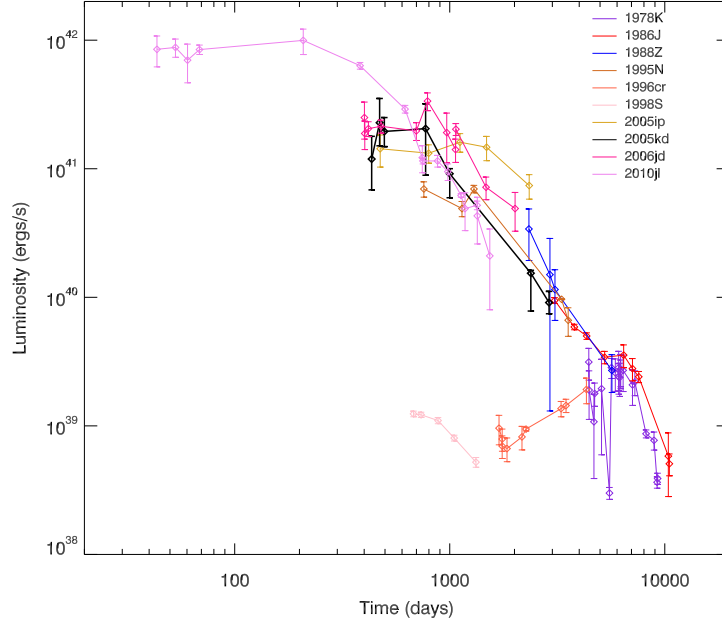
The time evolution of the luminosity can be related to the density structure of the surrounding medium, as shown in Fransson et al. (1996) and Dwarkadas & Gruszko (2012). To summarize, if we use the Chevalier (1982) description for a SN shock wave evolving in a self-similar manner, assuming spherical symmetry, the SN ejecta has a density that goes as  $\rho_{SN} \propto v^{-n} t^{-3}$ , and the uniform circumstellar medium into which the SN evolves has a density profile that decreases as  $\rho_{CSM} \propto r^{-s}$ , then the X-ray luminosity of the SN will decrease as

$$L_x \propto t^{-(12-7s+2ns-3n)/(n-s)} \quad (1)$$

or

$$L_x \propto t^{-(6-5s+2ns-3n)/(n-s)} \quad E \ll kT_{sh} \quad (2)$$

Equation 1 is valid when one is considering the total X-ray emission, equation 2 when one is considering the emission in an energy band  $E$  where  $E \ll kT_{sh}$ , and  $T_{sh}$  is the shock temperature. Neither is an exact fit to this situation; the latter is probably a better approximation over the first several hundred days, the former over the later period, but the resulting values are not significantly different using either equation. If we consider a luminosity decreasing as  $t^{-1.62 \pm 0.06}$ , we find that  $s$  varies between 2.3-2.46 for  $n = 9 - 12$ . Given the variation in parameters, we assume  $s = 2.4 \pm 0.1$  in our analysis. This range of  $s$  indicates that the density decreases marginally faster than  $r^{-2}$ , which would be the case for a wind with constant mass-loss rate and wind velocity. We note from figure 4 that this steeper decrease is not uncharacteristic of Type IIn SNe at this age; in fact many IInS appear to show a similar steep decrease in the lightcurves.



**Figure 4.** The lightcurves of observed Type IIIn X-ray SNe that have multiple exposures. For information on the data for each SN, the X-ray fluxes, and the bands referenced for each SN, refer to Dwarkadas & Gruszko (2012), from which this figure has been adapted, with several additions. SN 2005kd is shown with a thick black line. It's X-ray luminosity is high even among IIIn SNe, which in general have the highest luminosities of all X-ray detected SNe.

In order to calculate the mass-loss rate, we follow the procedure outlined in Fransson et al. (1996). Given the high temperature of the emission over most of the first 1000 days, we assume that it arises from the forward shocked circumstellar medium, and we do not see any emission from the reverse shocked ejecta (this is addressed later). We will calculate the quantity  $(\dot{M}/v_w)$  at a specific reference radius,  $10^{15}$  cm. We use the *XMM-Newton* observation given it has the best statistics. Following Fransson et al. (1996), we use the spectral luminosity at 1 keV. Since it is a spectral luminosity at a specific temperature, it is not modified by line emission, unless the line emission is present exactly at this frequency, which is not the case. We write the luminosity of the forward (circumstellar) shock as  $L_{cs} \sim j_{ff}(T_{cs})M_{cs}\rho_{cs}/m_H^2$ , where  $j_{ff}\rho_{cs}/m_H^2$  is the emissivity per unit mass,  $\rho_{cs}$  is the density behind the forward shock,  $M_{cs}$  is the mass swept-up by the forward shock, and  $T_{cs}$  is the temperature behind the forward shock. The Gaunt factor  $g_{ff}$  at 1 keV can be written as  $g_{ff} = 1.87 T_8^{0.264}$ , where  $T_8$  is the forward shock temperature  $T_{cs}$  in terms of  $10^8$  K. This approximation does not deviate by more than 30% from more accurately tabulated values at each temperature, as long as the energy  $E < 15$  keV, but may not be as appropriate for higher energies (Margon 1973). Using this value of  $g_{ff}$ , we can write the luminosity of the forward shock at 1 keV as:

$$L_{cs,1keV} = 1.4 \times 10^{38} \xi T_8^{-0.236} \frac{e^{-0.116/T_8}}{(3-s)} \left[ \frac{\dot{M}_{-5}}{v_{w1}} \right]^2 V_4^{3-2s} \left[ \frac{t_d}{11.57} \right]^{3-2s} \text{ ergs s}^{-1} \text{ keV}^{-1}. \quad (3)$$

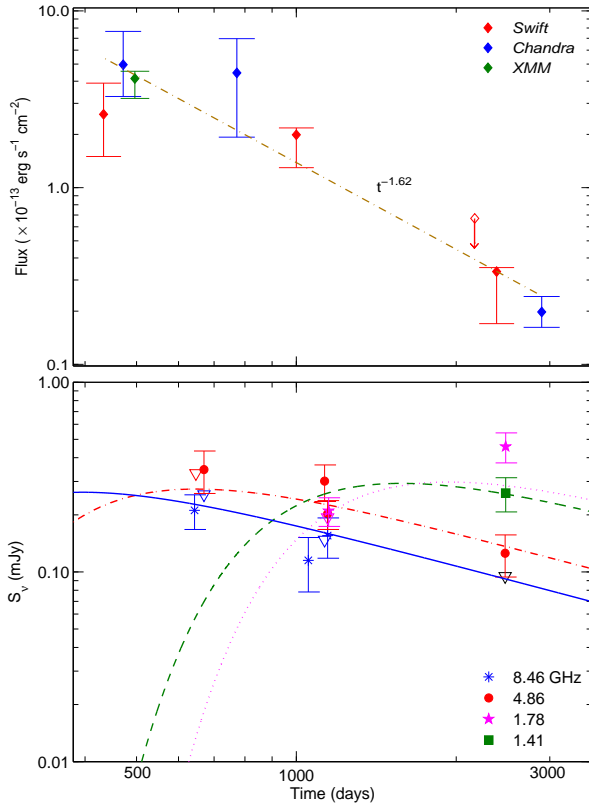
where  $\dot{M}_{-5}$  is the mass-loss rate scaled to  $10^{-5} M_\odot \text{ yr}^{-1}$ ,  $v_{w1}$  is the wind velocity in terms of  $10 \text{ km s}^{-1}$ ,  $V_4$  is the maximum ejecta velocity scaled to  $10^4 \text{ km s}^{-1}$ ,  $\xi = [1 + 2n(\text{He})/n(\text{H})]/[1 + 4n(\text{He})/n(\text{H})] \sim 0.85$ , and  $t_d$  is the time in days. We note that this expression has different approximations from the previous ones, and is independent of  $n$ . For  $s = 2.4$  it gives a flux decreasing as  $t^{-1.8}$ . It is close enough given the other uncertainties.

At 500 days, the average *XMM* flux at 1 keV is  $6.53^{+2.13}_{-1.73} \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}$ . Using a distance of 63.2 Mpc, and inserting in equation 3, with values of  $0.6 < V_4 < 0.9$ ,  $6 \leq T_8 \leq 9$ , and  $2.3 < s < 2.5$  in equation 3 gives

$$192 \leq \left[ \frac{\dot{M}_{-5}}{v_{w1}} \right] \leq 656. \quad (4)$$

Therefore we deduce that, for a wind velocity of  $10 \text{ km s}^{-1}$ , the mass-loss rate must be around  $(1.9-6.6) \times 10^{-3} M_\odot \text{ yr}^{-1}$  at  $10^{15}$  cm. If the wind velocity is higher, the mass-loss rate is correspondingly higher. It is difficult to find a progenitor that satisfies the velocity, mass-loss rate and light-curve characteristics (discussed in further detail in §6). We emphasize that the mass-loss rate is a time-varying quantity. However, it is clear that the ambient medium around the SN has a high density.

As described in §2, we have assumed thermal models to describe the SN, which are in ionization equilibrium. We can now go back and confirm if that approximation is reasonable. We note that we have calculated the mass-loss rate and wind velocity at  $10^{15}$  cm; thus the electron density at  $10^{15}$  cm is:



**Figure 3. (Top)** The 0.3-8 keV X-ray lightcurve of SN 2005kd (epochs listed in Table 1), showing unabsorbed flux with  $1\sigma$  error bars. The time is given in the rest frame of the SN, along with the k-corrected flux. The data comprise of 4 *Swift*, 3 *Chandra* and 1 *XMM-Newton* data-points. The best fit to the data is shown as a dashed line. It suggests the flux is decreasing as  $t^{-1.62 \pm 0.06}$ . **(Bottom)** Radio lightcurve of SN 2005kd at 8.46 GHz (blue, solid line), 4.86 GHz (red, dashed-dotted line), 1.78 GHz (green, dashed line) and 1.41 GHz (magenta, dotted line). Downward triangles represent  $3\sigma$  upper limits at the respective frequencies according to their color. The black triangle is the upper limit at 7.91 GHz. The error bars represent  $\pm 1\sigma$ . Where necessary, the flux has been converted to the appropriate frequency using the calculated radio spectral index. Fits to the data are shown and described further in §5. The few available data points do not allow for a robust fit, but the extracted parameter values are not inconsistent with those obtained from the X-ray data.

$$n_e = \left[ \frac{1}{4\pi \times 10^{30} \xi m_H} \right] \left[ \frac{\dot{M}}{v_w} \right] \sim (6.8 - 23) \times 10^9 \text{ cm}^{-3} \quad (5)$$

where  $m_H$  is the mass of a hydrogen atom. At any given radius, the density is  $(6.8 - 23) \times 10^9 (r_0/r)^s \text{ cm}^{-3}$ , where  $r_0 = 10^{15} \text{ cm}$ . We assume that for ionization equilibrium, the condition is that  $n_e t \sim 10^{12} \text{ cm}^{-3} \text{ s}$  (Smith & Hughes 2010).

At 500 days, assuming an average shock velocity of  $6000\text{--}9000 \text{ km s}^{-1}$  (appropriate for the high density), the shock radius is  $2.6\text{--}3.9 \times 10^{16} \text{ cm}$ . We have  $n_e t|_{500d} \sim (0.45 - 4) \times 10^{14} \text{ cm}^{-3} \text{ s}$  for  $s = 2.4$ . At 1000 days, assuming a slightly slower average velocity of  $5000\text{--}8000 \text{ km s}^{-1}$ , the shock radius is  $4.32 - 6.9 \times 10^{16} \text{ cm}$ , and the corresponding value is  $(2.26 - 23.6) \times 10^{13} \text{ cm}^{-3} \text{ s}$  for  $s = 2.4$ . For

$s = 2.5$  the density is somewhat lower, but still gives values  $> 10^{12} \text{ cm}^{-3} \text{ s}$ , whereas for  $s = 2.3$  the density is higher. In all cases we may conclude that the plasma is in ionization equilibrium at all times during which the observations were taken. A lower velocity will give a smaller radius and higher density so it will further reinforce this argument. Thus we can justify our use of models for plasma in ionization equilibrium.

Why do we not see (low-temperature) emission from the reverse shock, given that the temperature behind this shock is lower, and more likely to fall in the range of *Swift*, *XMM-Newton* and *Chandra*? Presumably it is because most of the emission from the reverse shock is absorbed. This is possible if the reverse shock is radiative and a cool dense shell has formed behind it, which absorbs the emission from the shock. The cooling time from the reverse shock can be written as:

$$t_{cool,r} = 3.5 \times 10^9 \frac{(4-s)(3-s)^{4.34}}{(n-3)(n-4)(n-s)^{3.34}} V_4^{3.34+s} \left[ \frac{\dot{M}_{-5}}{v_{w1}} \right]^{-1} \left[ \frac{t_d}{11.57} \right]^s \quad (6)$$

For  $2.3 < s < 2.5$ ,  $9 < n < 12$ , and  $V_4 < 1$  we find that the reverse shock is radiative throughout the evolution, for the derived values of  $\left[ \frac{\dot{M}_{-5}}{v_{w1}} \right]$ . Thus our initial assumption of the emission arising from the forward shock is validated. For large values of  $n$ , the cooling time goes as  $n^{-5.34}$  and thus is strongly dependent on the value of  $n$ . The shock will be radiative for any larger value of  $n$ .

Within the error bars, we find that the column density is  $3\text{--}10 \times 10^{21} \text{ cm}^{-2}$ , and decreases slowly over the first 1000 days. This suggests that there is some extra absorbing column density ahead of the forward shock too. Assuming the ambient density extends outwards continually with the same slope, the column density ahead of the circumstellar shock can be written as

$$N(H)_{cs} = 2.1 \times 10^{22} \left[ \frac{\dot{M}_{-5}}{(s-1)v_{w1}} \right] V_4^{1-s} \left[ \frac{t_d}{8.9} \right]^{1-s} \text{ cm}^{-2} \quad (7)$$

We note that this is the additional column that must be added to the value of the Galactic column density. For parameters between  $\left[ \frac{\dot{M}_{-5}}{v_{w1}} \right] \sim 192 - 656$ ,  $0.6 < V_4 < 0.9$ ,  $s = 2.3 - 2.5$  and  $t_d < 1000$ , this value starts off as a few to several times larger than the measured column of  $\sim 3 - 10 \times 10^{21}$ , and then slowly decreases, with the decrease being larger for higher values of  $s$  as expected from equation 7. For values of  $s = 2.4\text{--}2.5$  and the lower end of the mass-loss rate, the column density is generally less than the Galactic column by about 3000 days, and does not contribute much. For  $s = 2.3$ , the value is still larger than Galactic even at day 3000. For the top end of the mass-loss rate range, the values are quite high, especially for  $s=2.3$  and low  $V_4$ . The highest mass-loss rates are less likely, since we do not see such a large observed column, unless the medium is almost fully ionized (which is not the case as we show below). This implies that higher values of  $s$ , combined with mass-loss rates at the lower end of their appropriate range for high  $s$ , are more probable.

The timescale for recombination is  $\sim 3 \times 10^{12}/n_e \text{ s}$ . Using  $n_e$  from equation 5, we see that the circumstellar ma-

terial ionized by the progenitor star would have already recombined by the time the shock wave reaches it (see also Dwarkadas 2014). Hence the main mechanism for ionization of the medium is the X-ray emission itself, which depends on the ionization parameter  $\chi = L/nr^2$  (Kallman & McCray 1982). This can be written as:

$$\chi = 2 \times 10^{-38} L \xi^{-2} \left[ \frac{\dot{M}_{-5}}{v_{w1}} \right]^{-1} V_4^{s-2} \left[ \frac{t_d}{8.9} \right]^{s-2}. \quad (8)$$

Note that for  $s = 2$ , this becomes independent of time (if  $L$  is not time dependent), as expected. For the luminosities of 2005kd, and the high densities, the value of  $\chi$  should be less than 100 throughout most if not all of the evolution. For high temperatures outside the range probed by *Chandra* and *XMM-Newton*, e.g.  $T_8 \sim 10$ , Chevalier & Irwin (2012) find that elements such as C, N, and O are only ionized when  $\chi \sim 500$ . This indicates that even the elements like C, N, and O are not fully ionized in the high temperature plasma. Heavier elements such as Fe are only ionized at  $\chi \sim 5000$  (Chevalier & Irwin 2012). Overall the ionization factor is very low, which suggests that the medium is mainly neutral, and we are seeing almost the entire column that is present. The combination of equations 7 and 8 indicates a preference for higher values of  $s$ , which give higher ionization parameter and lower column, that is more consistent with the data.

## 5 RADIO EMISSION FROM 2005KD

In an attempt to further constrain the evolution, we have investigated the radio emission from the SN. We have analysed SN 2005kd radio data at three different bands obtained with the Very Large Array (VLA). Data reduction was done following standard procedures using the NRAO Astronomical Image Processing System (AIPS) for data taken in 2009 and earlier. For data taken after the VLA upgrade completion, we used the Common Astronomy Software Applications package (CASA; McMullin et al. 2007).

We used natural weighting in the imaging process of all the epochs to increase their sensitivity. Additionally there were observations at 22 GHz made in November 2005 and August 2007, but no detections were obtained. We do not discuss the emission at this frequency further since the limits provide no additional constraints.

The observations included here were made using 0410+769 as a phase calibrator. To test the reliability of the SN flux density variations, we made maps of the phase calibrator and measured a peak intensity of  $\sim 2.7$  Jy/beam for all the 4.5 GHz observations, and  $\sim 1.8$  Jy/beam at 8.5 GHz. At 4.5 GHz there is also a visible source at about  $1.2'$  West from SN 2005kd. This source has a flux density  $\sim 1$  mJy/beam in all those epochs. Thus, we consider the flux densities shown in Table 2 as highly robust measurements. The upper limits are given at a  $3\sigma$  confidence level.

The SN was detected as a point source, hence, the peak intensities shown in Table 2 also represent flux densities. The uncertainties include the contribution of the local r.m.s. and a conservative uncertainty in the absolute flux calibration of 5 per cent. We note that the 2007 August 14 epoch corresponds to the radio discovery reported by

Chandra & Soderberg (2007). Their value and the one we report here are consistent within the uncertainties. Furthermore, the epochs previous to the VLA upgrade in 2009 are limited by a poor dynamic range owing to the existence of other sources in the field which are much stronger than the SN itself. To account for this effect, we have carefully measured any background emission at the position of the SN in each epoch.

SN 2005kd was detected in the L, C and X bands over the first 9 years. The C and X band flux densities are decreasing with time, whereas the L band light curve appears to be still rising. Thus the radio emission appears to have already peaked at the higher frequencies and transitioned from the optically thick to the optically thin regime at 4.86 and 8.46 GHz, whereas it is perhaps still in the optically thick phase, or just transitioning to the optically thin phase at 1.4 GHz. This is consistent with observations of other radio SNe (Weiler et al. 2002). On 2012 August, the two-point spectral index between 4.49 and 1.78 GHz is  $\alpha = -0.72 \pm 0.35$ . Using this information, and assuming that the flux varied little between August 16 and 22, and that the spectral index extends from 1.78 to 4.86 GHz, we have converted the flux density measured on 2012 August 16 at 4.49 GHz to a flux at 4.86 GHz. The corresponding value is  $125.37 \pm 31.35 \mu\text{Jy/beam}$ .

We have fitted (see Figure 3) a multi-frequency light curve to the data shown in Table 2, following the parametrisation described in Weiler et al. (2002), using a Monte-Carlo simulation to obtain a robust fit (see details in Romero-Cañizales et al. 2014). We have adopted  $\alpha = -0.72$  and  $t_0 = 2005\text{-Nov-10}$  as explosion date (Tsvetkov 2008). The optically thick region is generally attributed to absorption by the external medium or the medium internal to the SN (free-free absorption, FFA) or due to synchrotron self-absorption (SSA). SN 2005kd displayed radio emission at late stages in its evolution, and a high but non-relativistic ejecta velocity (based on the X-ray temperatures in the first 1000 days). Hence, we exclude the contribution of a clumpy CSM (see e.g. van Dyk et al. 1994), as well as synchrotron self-absorption (Chandra et al. 2012; Romero-Cañizales et al. 2014) and consider FFA in the uniform local CSM. Thus, to represent the flux density evolution at a given frequency, we have used:

$$\left( \frac{S}{1 \text{ mJy}} \right) = K_1 \left( \frac{\nu}{5 \text{ GHz}} \right)^\alpha \left( \frac{t - t_0}{1 \text{ day}} \right)^\beta e^{-\tau_{\text{CSM}}} \quad (9)$$

where

$$\tau_{\text{CSM}} = K_2 \left( \frac{\nu}{5 \text{ GHz}} \right)^{-2.1} \left( \frac{t - t_0}{1 \text{ day}} \right)^\delta$$

. The fitted parameters ( $K_1 = 13.5\text{--}148.0$ ,  $K_2 = 2.4 \times 10^4\text{--}7.4 \times 10^7$ ,  $\beta = -0.74^{+0.16}_{-0.17}$  and  $\delta = -2.36^{+0.46}_{-0.66}$ ) allow us to infer a peak luminosity at 4.86 GHz of  $1.29 \times 10^{27}$  ergs  $\text{s}^{-1}$  on day 631 after explosion (rest frame). We thus estimate a mass loss rate of  $\sim 0.5 \times 10^{-4} M_\odot \text{ yr}^{-1}$  (assuming a wind velocity of  $10 \text{ km s}^{-1}$  and using equation 17 from Weiler et al. 2002) at a radius of  $\sim 4.6 \times 10^{16} \text{ cm}$ . The fit gives a value  $s = 1.82 \pm 0.37$ . This slope is a bit lower than our X-ray derived values. It is clear that there are problems with both the fit and its interpretation. The former is due to the sparsity



**Table 2.** VLA observations of SN 2005kd

Observation Date	Days after outburst (rest frame)	$\nu$ (GHz)	Conv. beam (arcsec <sup>2</sup> )	r.m.s. ( $\mu$ Jy/beam)	Peak intensity ( $\mu$ Jy/beam)
2007-Aug-14	632.5	8.46	$0.38 \times 0.29, -42.7^\circ$	42.42	$211.06 \pm 43.71$
2007-Sep-10	659.1	8.46	$0.37 \times 0.29, 40.3^\circ$	80.19	$< 255.85$
2008-Sep-27	1036.4	8.46	$0.37 \times 0.26, -35.9^\circ$	36.24	$115.09 \pm 36.69$
2008-Dec-13	1112.3	8.46	$0.39 \times 0.24, -36.5^\circ$	47.88	$< 147.47$
2008-Dec-28	1127.1	8.46	$0.36 \times 0.24, -20.4^\circ$	36.37	$155.36 \pm 37.19$
2012-Aug-16	2434.4	7.91	$1.47 \times 0.89, -2.2^\circ$	31.10	$< 94.92$
2007-Aug-18	636.4	4.86	$0.62 \times 0.44, -37.6^\circ$	82.41	$< 331.13$
2007-Sep-10	659.1	4.86	$0.58 \times 0.44, 38.2^\circ$	85.56	$346.57 \pm 87.30$
2008-Dec-13	1112.3	4.86	$0.93 \times 0.38, -42.3^\circ$	64.04	$300.91 \pm 65.78$
2008-Dec-28	1127.1	4.86	$0.74 \times 0.36, -33.0^\circ$	33.56	$202.54 \pm 35.05$
2012-Aug-16	2434.4	4.49	$2.57 \times 1.57, -2.0^\circ$	32.53	$132.80 \pm 33.20$
2008-Dec-28	1127.1	1.42	$2.66 \times 1.41, -45.3^\circ$	47.71	$< 193.57$
2009-Jan-02	1132.0	1.42	$2.52 \times 1.37, -6.7^\circ$	34.54	$209.94 \pm 36.10$
2012-Aug-22	2440.3	1.41	$6.71 \times 5.18, -178.2^\circ$	79.14	$458.04 \pm 82.39$
2012-Aug-22	2440.3	1.78	$5.32 \times 4.08, 1.1^\circ$	51.70	$269.40 \pm 53.31$

of data, which makes fitting unreliable; the latter is mainly due to the complexity of the system.

The smooth decline of the radio emission at both 4.86 and 8.46 GHz suggests a fairly smooth transition from 1000 to 3600 days. However, the long-lasting radio emission does favour the presence of an overall high density CSM, which is also inferred from the X-rays.

## 6 DISCUSSION AND CONCLUSIONS

In the previous section we form an overall picture of Type II<sub>n</sub> SN 2005kd. In our model the SN expands in a medium with a density slope  $s \sim 2.3-2.5$ , with a value of  $\left[\frac{\dot{M}-5}{v_{w1}}\right] \sim 192-656$  at a radius of  $10^{15}$  cm, and decreasing with time. The X-ray emission is likely dominated by the forward shock, with a high temperature and a column density that reflects the high mass-loss rate. The reverse shock remains radiative, with all emission from the reverse shock being absorbed by a presumed cool dense shell behind it. The data suggest a slight, although not conclusive, preference for higher values of  $s = 2.4-2.5$ , and lower mass-loss rates. Further observations are needed to confirm or refute this.

This analysis of the X-ray emission from a Type II<sub>n</sub> SN confirms that the SN expands into a very high density medium with density decreasing somewhat faster than  $r^{-2}$ . The density is higher than those encountered around the majority of stars. This is consistent with other Type II<sub>n</sub>s, although as we see from Figure 4, SN 2005kd's X-ray luminosity appears to exceed that of most Type II<sub>n</sub> SN. The instantaneous density at any given radius,  $\dot{M}_r$ , can be written as:  $\dot{M}_r \propto \dot{M}(r/r_0)^{2-s}$ . For  $s = 2.4$   $\dot{M}_r \propto (r/r_0)^{-0.4}$ . Thus the mass-loss rate at  $4.0 \times 10^{16}$  cm would be about 77% lower than that at  $10^{15}$  cm. Note that this indicates that the mass-loss rate was likely higher than  $10^{-4} M_\odot \text{ yr}^{-1}$  at  $4.0 \times 10^{16}$  cm.

The density profile is likely somewhat steeper than an  $r^{-2}$  density profile, indicating a variation in the wind parameters in the years leading up to the SN explosion. If we assume that the wind velocity was of order  $10 \text{ km s}^{-1}$ ,

then this variation occurred over at least the last 5000-7000 years of stellar evolution, suggesting that the progenitor star increased its mass-loss rate (and/or decreased the wind velocity) a few thousand years before explosion

It is hard to determine which progenitor best fits this analysis. The high mass-loss rate of  $0.43-1.5 \times 10^{-3} M_\odot \text{ yr}^{-1}$ , at  $4.0 \times 10^{16}$  cm, for a  $10 \text{ km s}^{-1}$  wind, is too high even for a red supergiant (RSG) star at the extreme high-mass end of mass-loss rates (Mauron & Josselin 2011). Humphreys et al. (1997) have shown that the yellow hypergiant IRC+10420 may have undergone high mass-loss episodes where it lost mass at a rate of  $10^{-3} M_\odot \text{ yr}^{-1}$  for about a 1000 years. This is lower than the time period of high mass-loss inferred by us for a wind velocity of  $\sim 10 \text{ km s}^{-1}$ , but not significantly so. It is possible that a hypergiant star with a somewhat higher mass-loss rate may just about meet the required characteristics at the lower end of the deduced mass-loss rate. The star must lose several solar masses of material in this period. The derived high Ca abundances are consistent with the finding that supergiant atmospheres are rich in Ca-Al silicates (Speck et al. 2000). A RSG or hypergiant progenitor is also compatible with the fact that the optical lightcurve from 2005kd showed a plateau for about 192 days (Tsvetkov 2008), indicating that it may arise from a progenitor with a large stellar radius. In this context it is interesting to note that, from an analysis of their R-band light, it has been found that the SNe II<sub>n</sub> population statistically bears more similarity to the SN IIP population than the SN Ic population (Habergham et al. 2014). The latter would be expected for really massive progenitors. The overall behaviour of SN 2005kd is reminiscent of other II<sub>n</sub>s that show photometric evolution similar to IIPs, as outlined in §1. Mauerhan et al. (2013) have defined a subclass of SNe called Type II<sub>n</sub>-P to describe these SNe that showed both II<sub>n</sub> and IIP characteristics. The energy radiated by all of these in the plateau phase must arise from circumstellar medium interaction, as demonstrated for SN 2005kd. As compared to the II<sub>n</sub>-Ps however, SN 2005kd shows a much longer plateau duration, and does not appear to decline as rapidly as the others at the end of the plateau phase. Unfortunately, the

lack of optical spectroscopy on SN 2005kd precludes more detailed comparison.

If the surrounding wind velocity were assumed to be much higher than  $10 \text{ km s}^{-1}$ , the mass-loss rate would need to be correspondingly higher, thus making it difficult to ascribe a known progenitor to the SN. LBVs have been suggested as II<sub>n</sub> progenitors. Their wind velocities are about an order of magnitude higher than those of RSGs, and consequently the required mass-loss rates would jump up by an order of magnitude. LBVs undergoing a giant eruption (Smith 2014) would be needed to satisfy the required mass-loss rates, which would exceed  $1 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$  for LBV wind velocities at  $4.0 \times 10^{16} \text{ cm}$ . The high mass-loss rates would also have to be sustained for several hundred years, which has generally not been observed in LBVs. Importantly, any progenitor without a large stellar radius as in RSGs would furthermore require a different explanation for the plateau region in the optical light curve. This could perhaps be a consequence of the SN being surrounded by a massive dense shell into which the shock expanded after breakout (Dessart et al. 2016). The shell would have to exist from a radius of around  $10^{16} \text{ cm}$ , given the current observations.

We have interpreted the obvious high density suggested by the observations as a high mass-loss rate (in equation 3). This however is not the only interpretation. A high density shell can also be due to sweeping up of external material by a lower density wind (Dwarkadas 2011). A similar model was found adequate to explain the X-ray emission from SN 1996cr (Dwarkadas et al. 2010). The decreasing light curve makes this appear less likely in the present case, however the lack of X-ray observations in the first 400 days makes it difficult to entirely rule out the possibility.

Figure 4 shows the similarity between the X-ray evolution of SN 2006jd and that of SN 2005kd. The X-ray luminosities are comparable. Chandra et al. (2012), in their interpretation of the X-ray lightcurve from SN 2006jd, have approximated it as a simple power-law decline, similar to our assumption here. Their derived densities were in excess of  $10^6 \text{ cm}^{-3}$  at 1000 days, comparable to the values found herein. The slope that they found was less steep than that found here, but overall the similarities between these two Type II<sub>n</sub>s are obvious.

In summary, SN2005kd provides further confirmation that II<sub>n</sub> SNe evolve in high mass-loss rate winds (Smith et al. 2007; Ofek et al. 2007; Chatzopoulos et al. 2011; Chandra et al. 2012; Fransson et al. 2014). They often appear to show rapid changes in wind parameters near the end of the star's lifetime. Such changes have also been postulated for many other Type II<sub>n</sub> SNe (Dwarkadas et al. 2010, and references within). The high mass-loss rates could just about accommodate a hypergiant star as a progenitor. An alternative possibility is that the surrounding wind velocity, and consequently mass-loss rate, are higher, and the progenitor is not a RSG that turned hypergiant but an LBV star undergoing a giant eruption, as has been often suggested for II<sub>n</sub>s. The latter though would require extremely high mass-loss rates to be sustained for at least several hundred years. Any progenitor model must also be able to account for the change in wind parameters in the years prior to the explosion, as well as the optically observed plateau region. Further continual and consistent monitoring of Type II<sub>n</sub> SNe at all wavelengths, but particularly in the X-ray and radio

bands, is suggested if we are to unambiguously determine their progenitors.

## ACKNOWLEDGMENTS

We acknowledge the anonymous referee for diligently reading the paper, and providing extremely valuable comments that have considerably improved the manuscript. The scientific results reported in this article are based on observations made by the *Chandra*, *Swift* and *XMM-Newton* X-ray observatories, and by the Very Large Array, NRAO Socorro, which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has made use of data obtained from the Chandra Data Archive and the HEASARC archive, and software provided by the Chandra X-ray Center (CXC) in the application packages CIAO, ChIPS, and Sherpa. We gratefully acknowledge support from grant GO4-15075X, provided by NASA through the Chandra X-ray Observatory center, operated by SAO under NASA contract NAS8-03060 (VVD, FEB); and from the NASA Astrophysics Data Analysis program grant NNX14AR63G awarded to University of Chicago (VVD). We also acknowledge support from CONICYT through FONDECYT grant 3150238 (CR-C) and from project IC120009 "Millennium Institute of Astrophysics" (MAS) funded by the Iniciativa Científica Milenio del Ministerio Economía, Fomento y Turismo de Chile (CR-C, FEB), from CONICYT-Chile grants Basal-CATA PFB-06/2007 (CR-C, FEB), FONDECYT 1141218 (FEB), PCCI 130074 (FEB), alma-conicyt 31100004 (CR-C, FEB), and "EMBIGGEN" Anillo ACT1101 (CR-C,FEB).

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